Applications of Aerospace Technology in Industry

A TECHNOLOGY TRANSFER PROFILE

WELDING

ACKNOWLEDGEMENTS

This technology transfer profile was prepared for the Technology Utilization Office, National Aeronautics and Space Administration by the Technology Management Group at Abt Associates Inc. under the direction of Warren D. Siemans, Project Supervisor. This report was written by David J. MacFadyen and Donald M. Murray. Louis Goldish of Technical Marketing Associates provided industry data for this report.

Much of the information was gathered with the assistance of NASA in-house and contractor personnel who participated in the development and application of the technology discussed.

APPLICATIONS OF AEROSPACE TECHNOLOGY IN INDUSTRY

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WELDING

- Prepared for -

The Technology Utilization Office
(Code KT)
National Aeronautics and Space Administration

Contract NASW-2022

- Prepared by -

Technology Management Group
Abt Associates Inc.
Cambridge, Massachusetts

September 1971

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1.0 INTRODUCTION

Welding was selected for a major role in the fabrication of U.S. space vehicles because of its advantages with respect to cost effectiveness and material weight, strength and volume.

However, weldability was not the sole criterion for the materials applied in spacecraft and launch vehicles, and there were some, such as heat-strengthened metals used in many rocket and spacecraft components, for which a controlled, reliable welding process had not previously been devised. NASA therefore found it necessary to refine and develop welding techniques whereby all the advantages of welding could be exploited and welds of consistently high quality could be achieved.

The NASA welding program's chief accomplishment and contribution to the science of welding was the formulation of a logical structure for analyzing the problems associated with critical joining applications. NASA took a unique approach to these problems in adopting the premise that testing and repair of defective welds was not practicable and thus the objective was to be reliability in the initial welds. Applying this concept, NASA technologists succeeded in producing welds of the desired quality, with only minimal repair and rework.

The program also generated numerous specific innovations many of which, along with NASA-developed techniques and NASA personnel, have found subsequent application in other segments of industry, where the impact of NASA's welding achievements is beginning to be felt.

2.0 OVERVIEW OF THE WELDING INDUSTRY

Modern Welding Techniques

Welding is defined by the American Welding Society as: "a metal joining process wherein coalescence is produced by heating to suitable temperature with or without the application of pressure, and with or without the use of filler material."

The techniques of metal joining have been evolving ever since prehistoric man began working with metals. There is evidence that men were soldering with binary alloys before 3000 BC, and metals have been joined by hammering since about 1400 BC. Over the centuries, as fabricated metal products became the building blocks of modern industrial society, the application and requirements of metal joining techniques proliferated. Today, welding as a metal joining technique is a basic process for almost all types of fabricated metal products.

While welding can be said to have a 5000 year history, its development was limited by the available sources of heat which, until about 200 years ago, consisted almost exclusively of wood and coal fires. The relatively low temperature of these fires was insufficient for all but the most elementary metal-joining methods.

It was not until the commercial availability of gas and electricity in the nineteenth century that welding as it is known today began to develop. The nineteenth century saw the development of the basic gas and electric welding processes, while in the twentieth century, the many refinements of these processes, which comprise the techniques of modern welding, were introduced (Exhibit 1). Today almost 50 welding processes are used by industry (Exhibit 2). Some of these, particularly the "cold" welding processes such as ultrasonic bonding, go beyond the basic "heat-oriented" definition of welding.

There are, today, few areas of metal fabricating which do not involve welding in some way, from joining almost microscopic electronic components to joining structural members for skyscrapers, with welded joints appearing as little dots on thin foil or as long seams on ship hulls. Welding is used to create works of art, to repair cracks in massive machine gears, to join seams in garbage cans, as

EXHIBIT 1

THE HISTORICAL DEVELOPMENT OF MODERN WELDING PROCESSES

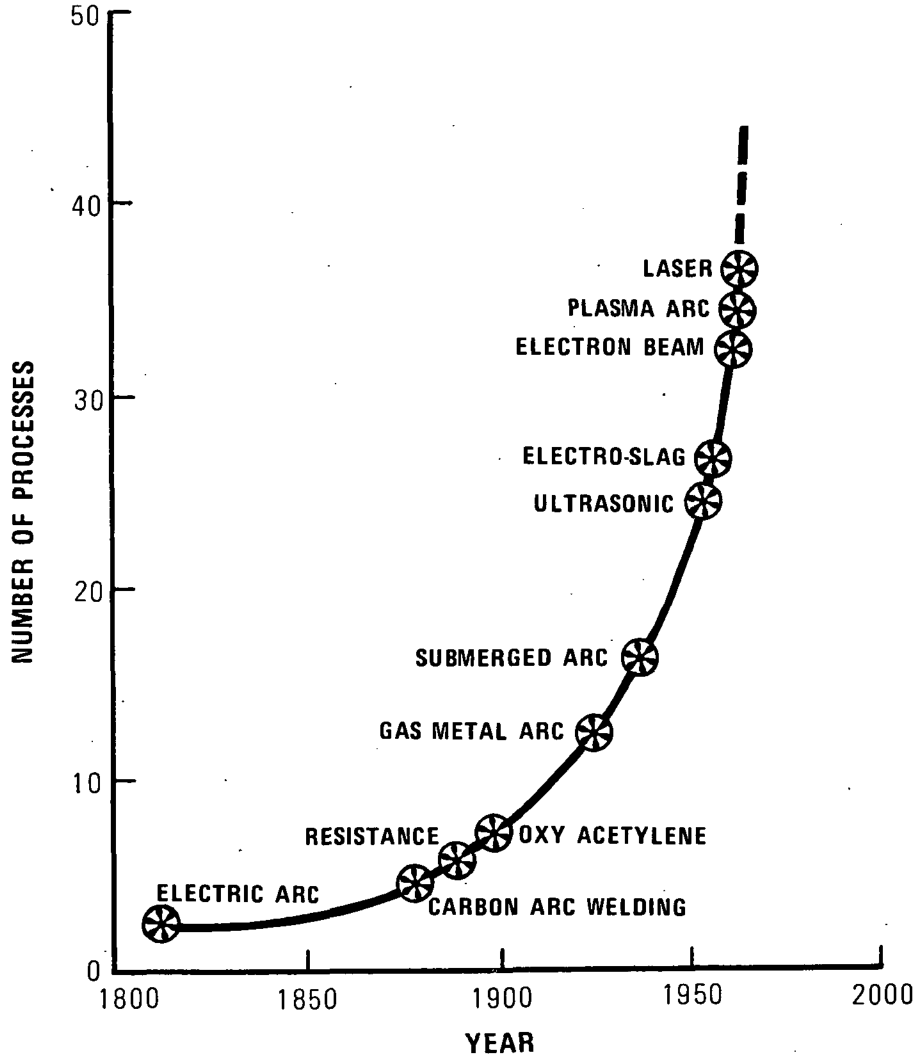
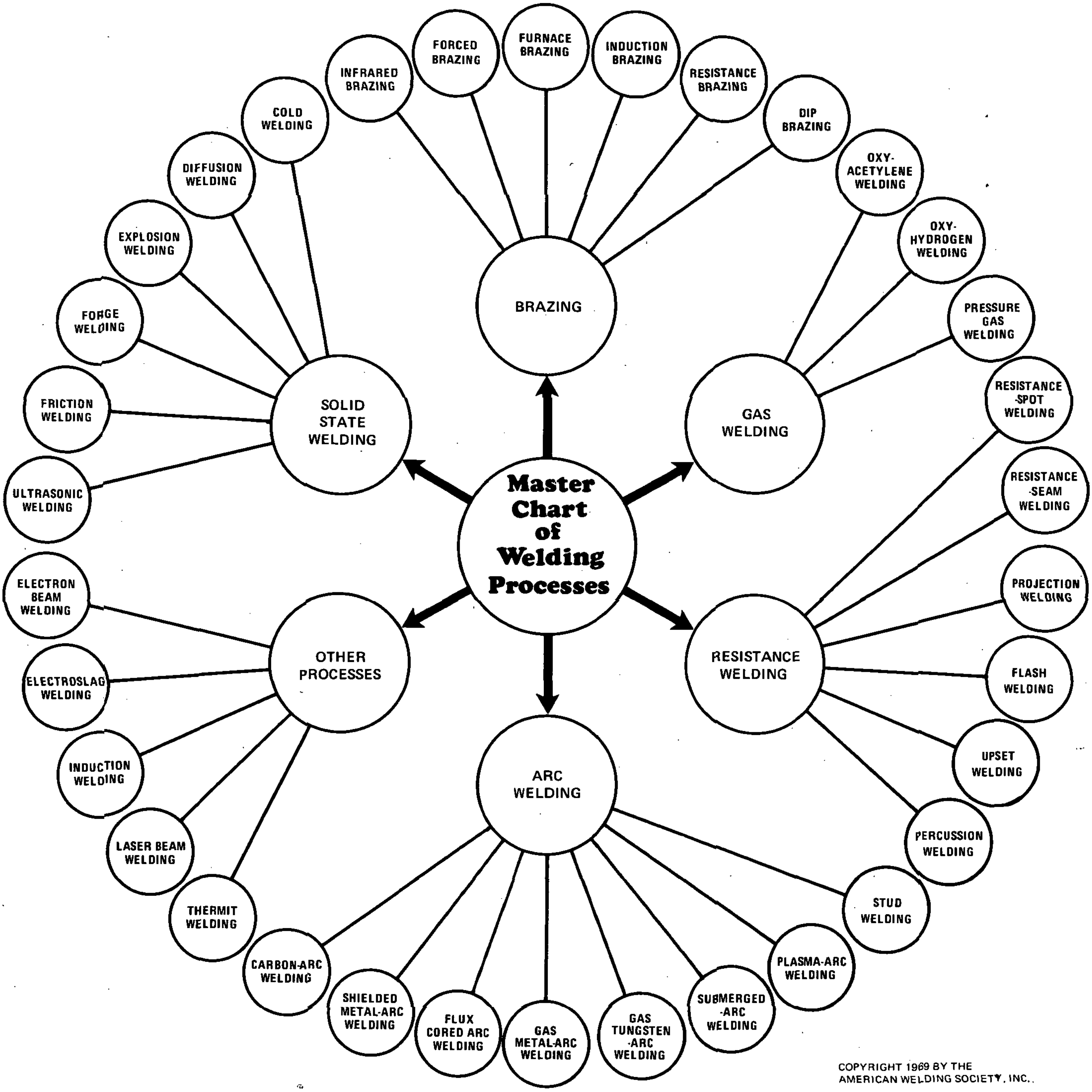


Chart from *The History of Welding* by R. D. Simonson (Monticello Books, Inc., 1969).

EXHIBIT 2

CHART OF WELDING PROCESSES



Other Processes Include:

- Explosive bonding
- Plasma-arc welding
- Electron-beam welding
- Laser welding
- Explosive bonding
- Electroslag welding
- Ultrasonic welding
- Inertia welding
- Diffusion bonding

Chart from Current Welding Processes (American Welding Society, 1964) well as in space capsules. It is to meet the many different requirements for metal joining that the wide variety of welding techniques has been developed.

The three basic types of welding, gas welding, arc welding and resistance welding, are used for over 90% of all welding performed today. While there are many variations of these basic processes, all rely upon fusion joining whereby metal is heated to a molten state, and a solid joint is formed upon solidification.

Gas Welding

Gas welding utilizes the combustion of flammable gases to produce a flame hot enough to melt metal. The gases are usually burned in a torch which, in addition to mixing the proper amounts of gas, concentrates the flame so that a large amount of heat is available in a small area. The most common form of gas welding is oxy-acetylene welding whereby acetylene is burned with oxygen to produce a flame having a temperature on the order of 6000 degrees F. The parts to be joined are heated, and a filler metal rod is melted into the joint.

Because gas welding is a slow process compared to other modern welding methods, it has been displaced to a great extent as a production technique. However, the skills of gas welding are easy to master, and the basic equipment is relatively inexpensive: on the order of $150 for the torch, regulators and hose connections. Consequently, gas welding is extremely popular for repair and maintenance work and for light fabrication. Gas welding equipment can also be used as a versatile metal cutting tool -- the familiar cutting torch.

Resistance Welding

Resistance welding is accomplished by passing a very high-amperage electric current through the areas to be joined. The current is applied with electrodes, which, at the same time, apply pressure to the joint. The heat generated by the electrical resistance losses of the metal to be welded fuses the joint. No filler material is required.

Resistance welding is currently applied in three principal ways. In spot welding, sheets are joined by fused spots, created by passing high current through electrodes which hold together the sheets to be welded. For seam welding, a rotating electrode wheel is used to produce a seam which consists essentially of a line of spot welds. Such a process is used for welding tubing. Flash welding is commonly used for welding bars end to end, and the bars themselves are used as the electrodes. The current passing between the contact points melts the metal, and the two bars are then squeezed together to form the weld.

Today, the resistance welding process is widely used for manufacturing products built of sheet metal assemblies such as automobile bodies and appliance cabinets.

Another welding process utilizing the inherent resistance of metal to passage of electric current is induction welding. A high-frequency electric current is induced in the joint to be welded, and the heat of fusion is produced by the resistance of the metal to current flow. Induction welding is used for high-speed joining of tube seams and for welding closed structural shapes.

Arc Welding

Arc welding is the principal and most widely used industrial welding process. Heat is generated by an electric arc which passes between a welding electrode and the metal pieces to be joined. The heat of the arc melts the edges of the pieces, fusing the joint. The fusion and subsequent solidification occurs very rapidly, allowing for relatively high speed linear welding. This speed is one of the reasons for the popularity of arc welding in industry.

Currently there are fourteen conventional arc welding processes, which differ principally in the way harmful gases are excluded from the weld area. However, these can be classified into five principal categories, each of which is used for specific applications, depending upon the material to be welded, the type of welding being performed, and the desired weld characteristics:

Shielded-Metal-Arc Welding: Shielded-metal-arc welding utilizes a coated electrode. The coating vaporizes in the arc producing a gas which shields the weld puddle.

Tungsten Inert Gas (TIG)/Gas Tungsten Arc Welding (GTA): TIG welding utilizes an arc generated by a non-consumable tungsten electrode with an auxiliary wire providing the filler material where required. The weld puddle is shielded by a flow of inert gas.

Metal Inert Gas (MIG)/Gas Metal Arc Welding (GMA): MIG welding is similar to TIG welding but utilizes a consumable electrode. Like TIG welding, the weld puddle is shielded by an inert gas.

Other Welding Processes

Electroslag Welding: Electroslag welding generates heat by passing an electric current through a pool of molten slag. The slag melts the faces of the joint and the electrode to form the weld pool. The pool is held against the joint to be welded by means of a water-cooled "dam."

Since the ability to weld in the vertical position is not available from most other welding techniques, electroslag welding has been found to be a useful tool by shipyards and fabricators of structures and pressure vessels.

Plasma Arc Welding: Plasma arc welding utilizes a gaseous arc in a manner similar to that of the TIG arc.

Electron Beam Welding: Electron beam welding employs a narrow, focused beam of electrons which impinges upon the joint to be welded to melt the joint edges and fuse them.

Laser Welding: Laser welding utilizes the energy from a highly focused, high-energy beam of light to provide the fusion energy necessary for welding. The application method of laser welding, that of welding by means of a focused beam, is similar to that of electron beam welding.

Ultrasonic Welding: Ultrasonic welding is essentially a cold welding process which utilizes ultrasonic energy and pressure to form an interatomic bond. The ultrasonic bond is made with little or no melting and does not require filler material.

Diffusion Bonding: In diffusion welding, heat and pressure are applied to highly cleaned, perfectly mated surfaces so that the surfaces fuse together by the process of atomic diffusion.

Industry Trends

Development and application trends in the welding industry have been directed toward:

(a) Faster welding speeds.

(b) Higher quality, more reliable welds.

(c) The ability to weld hitherto unweldable materials.

(d) Diminishing weld costs.

(e) More extensive applications of welding as a metal joining technique.

(f) Automation of welding.

It is expected that the welding processes which are already in widest use, namely arc welding and its variations, will continue to dominate the welding industry. However, the continued introduction of new metals and alloys into commonly manufactured products will require improvements and advances in conventional welding techniques.

As further economies of production are introduced for fabricated products, welding may be used as a replacement for casting, forging, bolting, or riveting on a variety of fabricated metal products. Techniques yielding more reliable and more controllable welds will be utilized.

In the past twenty years there has been an amazing number of new developments in welding. Much of this work can be traced to government funding to meet the requirements of space programs and defense commitments. In industry, the emphasis has been on automation of existing processes. In many cases the two efforts, that of space and that of private industry, have merged where the development work in one program has produced benefits in both areas. Recent advances in TIG welding exemplify a development of this type.

TIG welding was originally developed for the welding of aircraft during World War II. Industry rapidly adopted the process, and automatic or semi-automatic systems were devised for both military and industrial applications. The latest adaptation is the incorporation of numerical control equipment, such as has been used successfully on machine tools with the TIG automatic welding process. The numerically controlled TIG welding machine, announced in 1966, was developed by Sciaky Brothers and Bendix Corporation for the Douglas Missile and Space Systems Division.

Many other processes have been adapted from the welding of steel to the welding of aluminum. The highly automated automative-type spot welding has now been taken one step further to meet aerospace requirements. Again, it has been the incorporation of numerical control by Siaky Brothers, this time from Boeing Aircraft Company.

Even more spectacular than the gradual increase in automation which was assisted by the aerospace efforts has been the proliferation of newer welding processes to meet the challenges posed by the space effort. In the pursuit of our space activities new and unusual metal alloys were required, and new and unusual welding processes were needed to join them. Developments in the plasma, electron beam and laser processes have accelerated as a result.

In the production of space vehicles, metals were chosen for many characteristics, only one of which was weldability; thus metals were frequently chosen which were not the alloys most amenable to welding. This necessitated the development of new welding processes for these materials. But the attitude toward welding has changed over the years, and the metal industry, which used to label metals weldable or nonweldable, has gradually adopted the concept of weldability of metals. Although the metals chosen for the space effort frequently were weldable, they were, at the same time, difficult to weld. The largest and most complex welding jobs were performed on aluminum alloys. The developments introduced will have widespread implications for the fabrication of aluminum materials.

Characteristics of the Aluminum Industry

The demand for aluminum, both in the United States and internationally, is growing at a high rate. The historical U.S. aluminum industry growth rate average of 7.6%, which has prevailed since 1950, has been exceeded during recent years. Between 1961 and 1965 the increase averaged 13% per year. Aluminum authorities believe that demand for aluminum by 1975 will be twice that of 1965. Production of aluminum alloy welding electrodes increased from approximately 1/2 million pounds in 1950 to 10-1/2 million pounds in 1965, a twenty-fold increase. This is expected to increase to 35 million pounds by 1980, more than triple the 1965 level.

The uses of aluminum fall into many markets. In building and construction activities, aluminum is used in residential, industrial and commercial and farm applications. Doors, windows and screenings, awnings and canopies, roofing and siding, curtain walls and store fronts, gutters, downspouts, bridge structures and guard rails, lighting standards and mobile homes are common uses of aluminum in construction. Little of this is welded construction. The next largest aluminum market is for transportation equipment, much of which is welded. The aerospace and aircraft industries, ships and small boats, rail cars, truck bodies, automotive applications, travel trailers and recreational vehicles, and many other types of cargo containers are fabricated of aluminum. Many of these products utilize aluminum welding. The consumer durable goods market includes refrigerators, air conditioners, cooking utensils, furniture, pleasure boats, and personal and recreational goods. Many of these products can benefit from recent advances in welding technology. Aluminum applications in the electrical industry comprise electrical equipment in machinery, lighting fixtures and electric lamps, power transmission and distribution equipment and communications equipment. Machinery and equipment uses include agricultural, construction, and industrial and mining machinery. Irrigation pipe, storage tanks, especially containers for cryogenic materials, sewage disposal process industry equipment, fasteners and general components are other users of aluminum. Finally, aluminum is used in cans, semi-rigid food containers, household and institutional foil, caps and closures, collapsible tubes, and many flexible packing items.

The applications of aluminum relate to its electrical and its structural characteristics. Those applications which require aluminum's high strength-to-weight ratio for structural economy are the areas in which we may expect the advances in aluminum welding technology to be of greatest benefit. In transportation equipment such as ships, truck transport, railroad cars, or even dump trucks, there are maximum weight limitations. Thus every pound of material used in the construction of the equipment reduces the load-carrying capacity by one pound. Since the ratio of strength to weight for aluminum is roughly three times that of steel, equipment constructed of aluminum weighs significantly less than steel equipment. Although steel in the past has had the competitive advantage in fabrication because of the ease with which it is formed and welded, new, improved processes for welding aluminum may reduce even these differences.

A recently completed study of the performance of aluminum welding equipment indicated that there are problems in the equipment which can be overcome in order to improve the aluminum welding process. Industry's problems included: the feeder wire drives for MIG welding equipment; welding defects caused by arcing in the tube of the welding gun; inadequate service by equipment suppliers; non-uniformity of equipment and shortages of replacement parts; poor wear characteristics of parts of the equipment; failures of welding gun motors; welding guns too heavy for position welding; gauges that cannot be read from a distance; TIG welding components that are not sufficiently rugged for production conditions; and side-effects such as the burn-out of auxiliary equipment due to high-frequency leakage in TIG equipment. The participants in the survey were manufacturers of military equipment, pressure vessels, storage tanks, pipe, tank transports, boats, rail cars, ships and other equipment. The introduction of improved welding techniques could significantly improve their business and make their products more competitive. As the newer aluminum welding techniques are developed and become commerically applicable, we can anticipate the availability of less expensive, improved aluminum equipment.

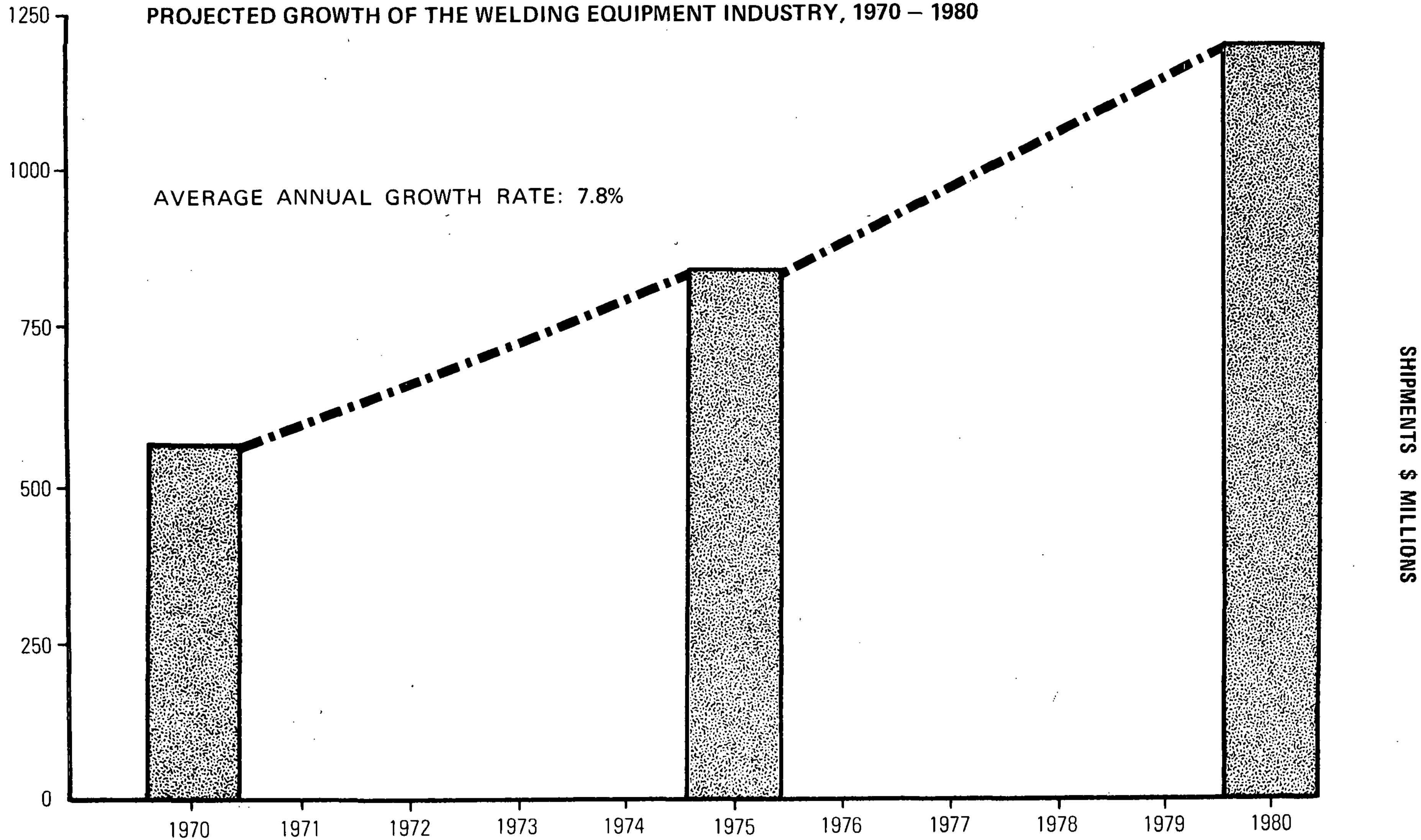
Market Sizes and Growth Rates

The true impact of welding is to be measured in the value of parts produced by welding, in the amount of money saved by the use of welding over other metal fabrication processes, and in the value of products made possible by welding. However, even the historical and projected growth rate of the welding equipment industry provides some measure of the significance of welding.

The welding equipment industry has been growing at approximately 6% annually for the past five years, and industry shipments are currently at about $565-million (Exhibit 3). Conventional electric welding equipment and supplies currently comprise over three-quarters of this market.

EXHIBIT 3

PROJECTED GROWTH OF THE WELDING EQUIPMENT INDUSTRY, 1970 – 1980



(Source: U. S. Department of Commerce)

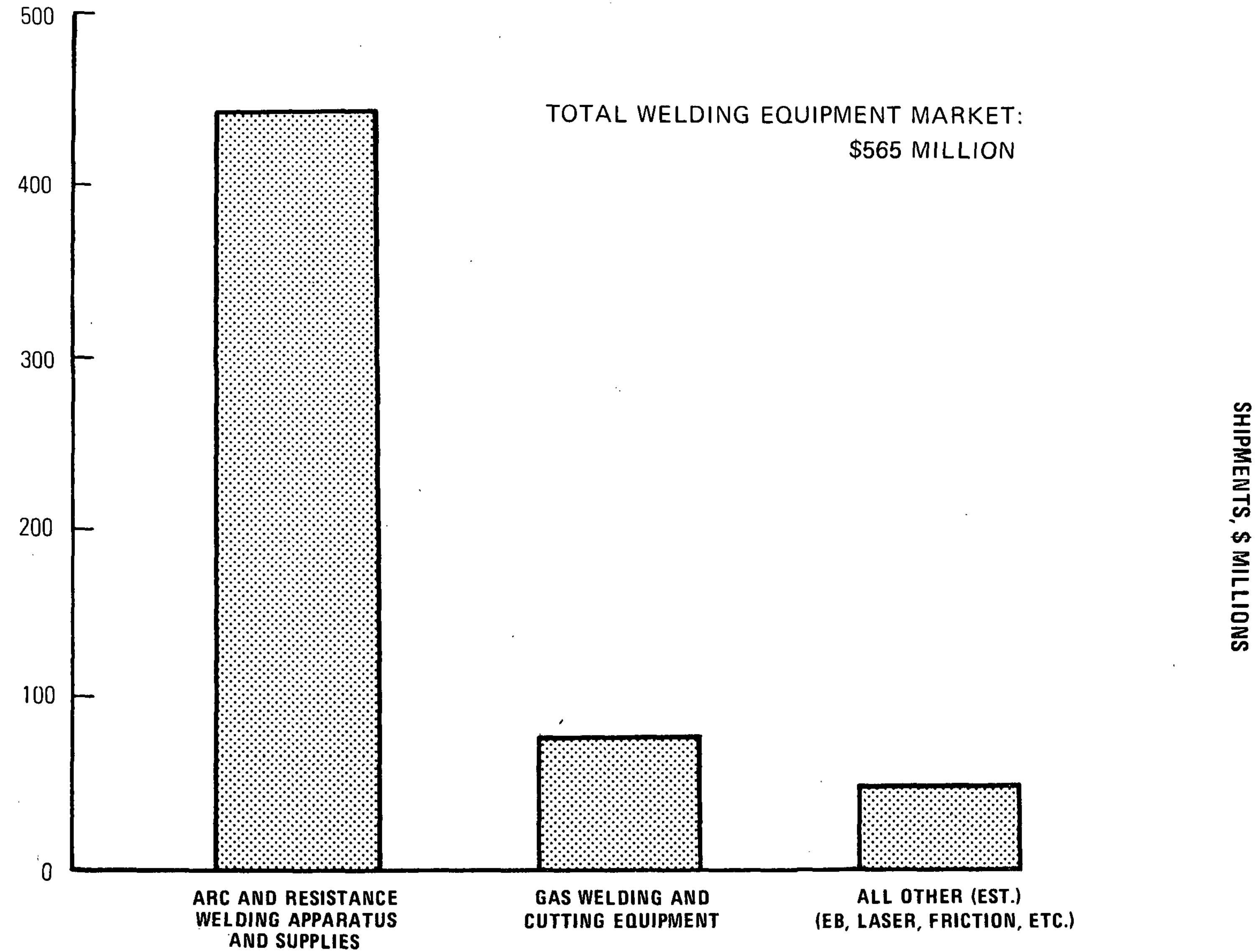
(Exhibit 4). Increased emphasis on welding as a basic manufacturing technique is expected to boost this growth rate to approximately 7.8% annually, and welding equipment shipments are expected to more than double by 1980. (Exhibit 5).

While welding techniques such as electron beam welding, laser welding, friction welding, fusion welding and ultrasonic welding will see wider use in specialized applications, it is still expected that these techniques will comprise only a fraction of the total welding market.

The electron beam welding equipment market totaled $9.3 million in 1965, $28.0 million in 1970 and is predicted to reach $50 million by 1980. Lasers are predicted to grow even more rapidly from $700,000 in 1965 to $4 million in 1970, to $70.0 million in 1980.

EXHIBIT 4

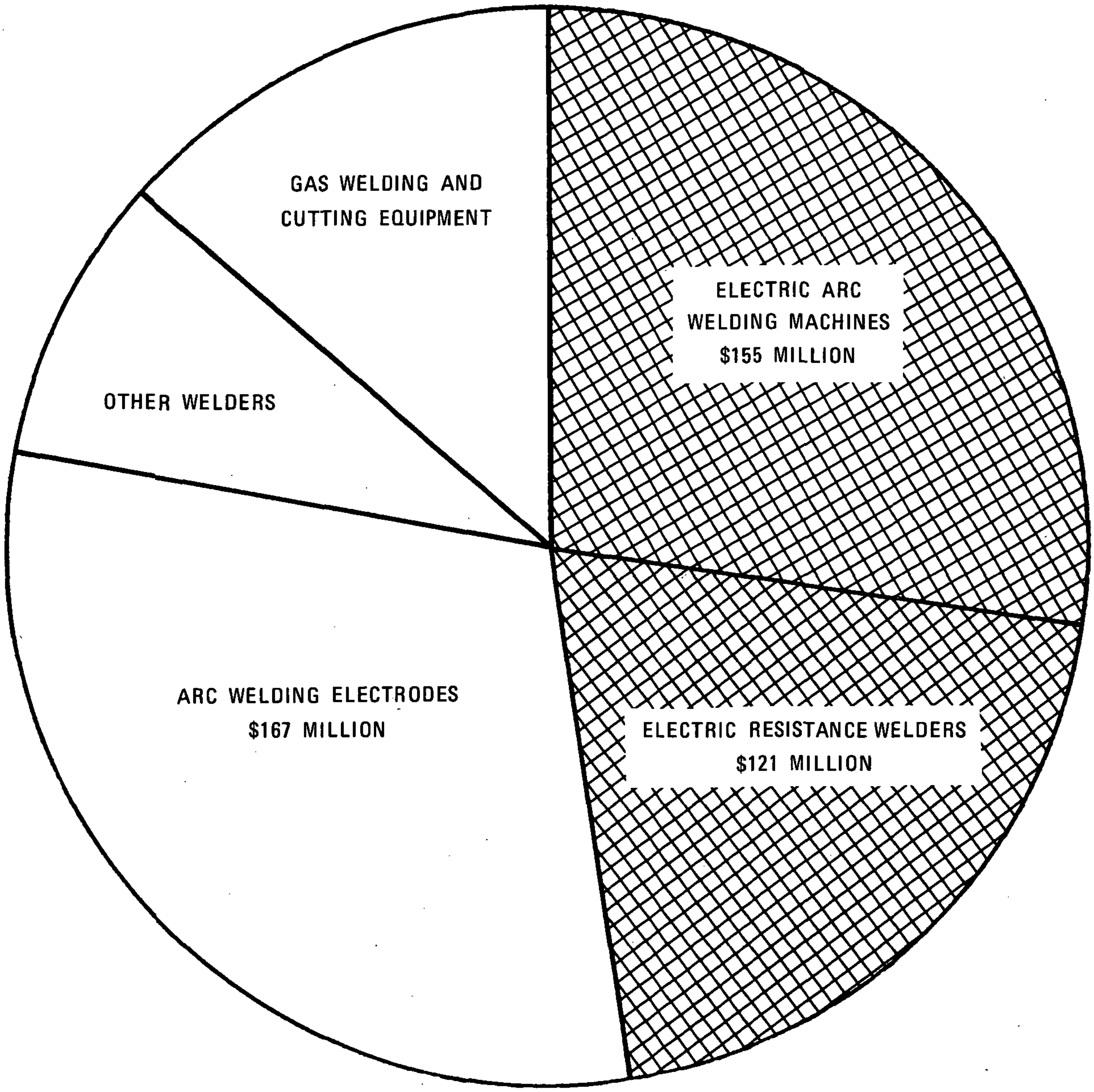
ESTIMATED SALES OF WELDING EQUIPMENT BY GENERAL CLASS, 1970



(Source: U.S. Department of Commerce)

EXHIBIT 5

DISTRIBUTION OF SHIPMENTS OF CONVENTIONAL WELDING EQUIPMENT



TOTAL SHIPPING: $565 MILLION *(Source: U.S. Department of Commerce)*

3.0 NASA'S CONTRIBUTION TO WELDING

The field of welding has been a major beneficiary of the technological advances made in the course of the NASA space program. Contributions to the state-of-the-art have ranged from very basic concepts of the metallurgical mechanics of metal joining processes to the development of reliable processes for the rapid production of weldments. The joining of high-strength and lightweight alloys to produce the large and reliable structures required was a task of such magnitude that the welding of high-strength aluminum performed by NASA was actually a production process. Thousands of inches of weld were required. While there was a great deal of production-type welding, some welding work was accomplished on a low-volume or one-time basis. These more specialized and unique welding requirements also called for new processes and equipment. The thrust of this report will be the production-type welding that was used at the Marshall Space Flight Center in the construction of the large Saturn launch vehicle. The work performed in other areas of welding will only be described briefly.

3.1 Technological Progress

The mechanism of technological progress has changed considerably in recent years. Whereas in the past an entire product or process could be attributed to an individual inventor, today technological advance is a highly specialized process involving many contributors. No one individual in most instances, is responsible for a major breakthrough. Rather, it is the cumulation of numerous small contributions which raises a discipline to a superior level of performance, as evidenced by the hundreds of technical journals which monthly and quarterly record the incremental steps. The evolution is slow and laborious, with the more rapid advances requiring some ten to fifteen years between the initial discussion stage and actual application of a technology in a production process. This being the case, it is exceedingly difficult to document accurately the sequence of steps leading to a technological breakthrough, or to identify the single most important contribution.

Perhaps the major portion of the credit for a scientific or technological adance belongs to those who construct the framework within which a critical problem can be researched and solved. In delineating the problem and its components and providing guidelines for research and applications engineering, they have made an invaluable contribution, regardless of their participation in the final stages of solving the problem.

The work of organizing the problem for orderly research allows for application of old concepts in new areas. When a problem is carefully analyzed and explicitly stated, it is frequently found that technology previously developed for other purposes can be applied to the problem, thus obviating the search for new concepts. Valuable time, effort and funds are saved by utilizing existing knowledge rather than embarking on a basic research program. This is not to imply that application of an existing concept to a new context does not involve research and extensive applications engineering. It does mean, however, that we can bypass the laborious process of examining and screening a multitude of technological concepts before arriving at one which answers the stated problem.

In those instances where no existing technology is found to be applicable to the problem at hand, a search for a new concept must be undertaken. Encountering such problems in their welding program, NASA technologists successfully formulated a number of important new concepts to arrive at the ultimate solution. In other instances, new concepts surfaced in the course of applications engineering efforts to apply existing technology to new problems. One such concept, described in detail below, was the discovery that process control is absolutely essential in achieving fundamentally good welding.

The necessary foundation for any major research program is a rich fund of accurate source data. The subsequent data analysis provides the researcher with both valuable guidelines for action and a basic understanding of the characteristics required for an effective solution to the problem. In order to examine the maximum number of possible solutions at minimum cost, a methodology for accurate analysis is required. Therefore, when current analytical techniques prove inadequate for the task, new methods must be developed, frequently in the form of computer programs. Many cases will call for new testing and measuring techniques, and on occasion it is necessary to devise new instruments for the required measuring. In summary then, the task of establishing good data sources, of researching past work, devising testing methods, and sharpening analytical tools is equally important, and frequently of the same magnitude as the applications engineering effort directly related to solving the problem. Achievement of an effective solution to the problem may further necessitate very basic research into the underlying scientific principles of the subject. NASA's welding program has encompassed all these various activities.

3.2 NASA's Program to Improve Aluminum Production Type Weldments

The start of a coordinated effort to solve the common welding problems relevant to construction of the Saturn V launch vehicle was a NASA survey of welding problems conducted among technologists at the Marshall Space Flight Center and eleven associated contractors. In addition, a tabulation was made of studies then underway to correct problems in welding high-strength aluminum. It was found that the majority of aluminum welding problems required research on the level of basic study, which individual producers were unlikely to perform. The problems and studies were grouped into five categories, each of which included numerous problem definitions:

(1) Welding parameters and techniques
(2) Welding equipment and instrumentation
(3) Inspection and defect detection
(4) Materials and material preparation
(5) Miscellaneous

The survey also included an analysis of the procedures employed by Marshall Space Flight Center and by each contractor.*

*Hoppes, R. V., Survey of Aluminum Welding Problems in Aerospace Industry, Huntsville, Alabama: Manufacturing and Technology Division, Manufacturing Engineering Laboratory, George C. Marshall Space Flight Center, May 1964.

NASA then undertook the solution of many of the welding problems revealed in their survey.

Three main areas of activity were pursued to improve the performance and reliability of high-strength aluminum welds; and to correct problems in the five problem areas stated above.

(1) Improvement of the strength of welded joints

(2) Reduction of thermal effects on welding and weldment behavior

(3) Improvement of quality control

Exhibit 6 displays the three areas of investigation, with the breakdown of individual problems and the NASA contracts aimed at their solution. This represents the general framework within which improvement of high-strength aluminum welds was pursued. Provision of such guidelines for the orderly development of this technology greatly facilitated the task of constructing the large welded aluminum structures for the space program. Significant improvements in welding have already been achieved via this methodology, and it should certainly enhance the efficiency of future pursuits in the field. The same framework of inquiry is applicable to the entire gamut of joining processes -- welding of mild steel, high-strength steel, stainless steels, aluminum of all types, magnesium, titanium, and even the adhesive joining of structural elements. The scientific approach to the improvement of aluminum welds and the concept of process control are major contributions to the field of welding, and they should find broad application in industry.

Specific contributions to the state-of-the-art which resulted from application of the scientific method described above include the development of weld strength, residual stress and distortion control, and the establishment of process control parameters.

Professor Masubuchi has integrated the various studies and delineated many of NASA's specific technical contributions to the welding of heat-strengthened aluminum.*

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Masubuchi, Koichi, Integration of NASA-Sponsored Studies on Aluminum Welding, Columbus, Ohio: Battelle Memorial Institute, September 1967.

Masubuchi, Koichi, Integration of NASA-Sponsored Studies on Aluminum Welding, Second Edition, Cambridge, Mass.: Department of Ocean Engineering, Massachusetts Institute of Technology, June 1971.

Improving Weld Strength

Efforts to improve weld strength centered on reducing weld porosity and its effect on the mechanical behavior of weldments. Of the defects encountered on four first-stages of Saturn V, 79% were porosity-related, with cracks ranking second at 9%. Hydrogen has been considered the prime source of the porosity to which high-strength aluminum alloys are so susceptible. Following extensive studies on the subject, process control measures were introduced to minimize porosity. These included cleaning the surfaces of the metals to be joined and the filler wire, verifying the chemical composition of the metals and the filler wire, ensuring the purity of the shielding gases, and precisely controlling the means of aligning and handling the metal parts.

None of the various nondestructive testing techniques customarily used for detecting porosity in structural welds was entirely satisfactory. It was therefore necessary to identify and eliminate from the welding process factors capable of creating porosity. Numerous studies were undertaken to arrive at an understanding of the basic mechanisms involved in the creation of porosity and its effects on weld strength.

Professor Masubuchi has applied the well developed theory of stress concentration around cavities in a discussion of the strength-reducing characteristics of various sized pores introduced by the welding process.* This theory has been applied to numerous materials. It provides valuable insight into the behavior of porous welds by clarifying the role of pores and the relationship between pore size and strength reduction.

Studies 1 (Shielding-Gas Contamination) and 5 (Mechanisms of Porosity) in Exhibit 6 examined the effects of porosity on weld joint performance under static loading. These testing programs verified that the loss of strength due to porosity in aluminum welds was proportional to the reduction of sectional area, as long as all pores were counted. This is a result that would be anticipated from an analysis of the effects of cracks, voids or pores in aluminum. Initial test results

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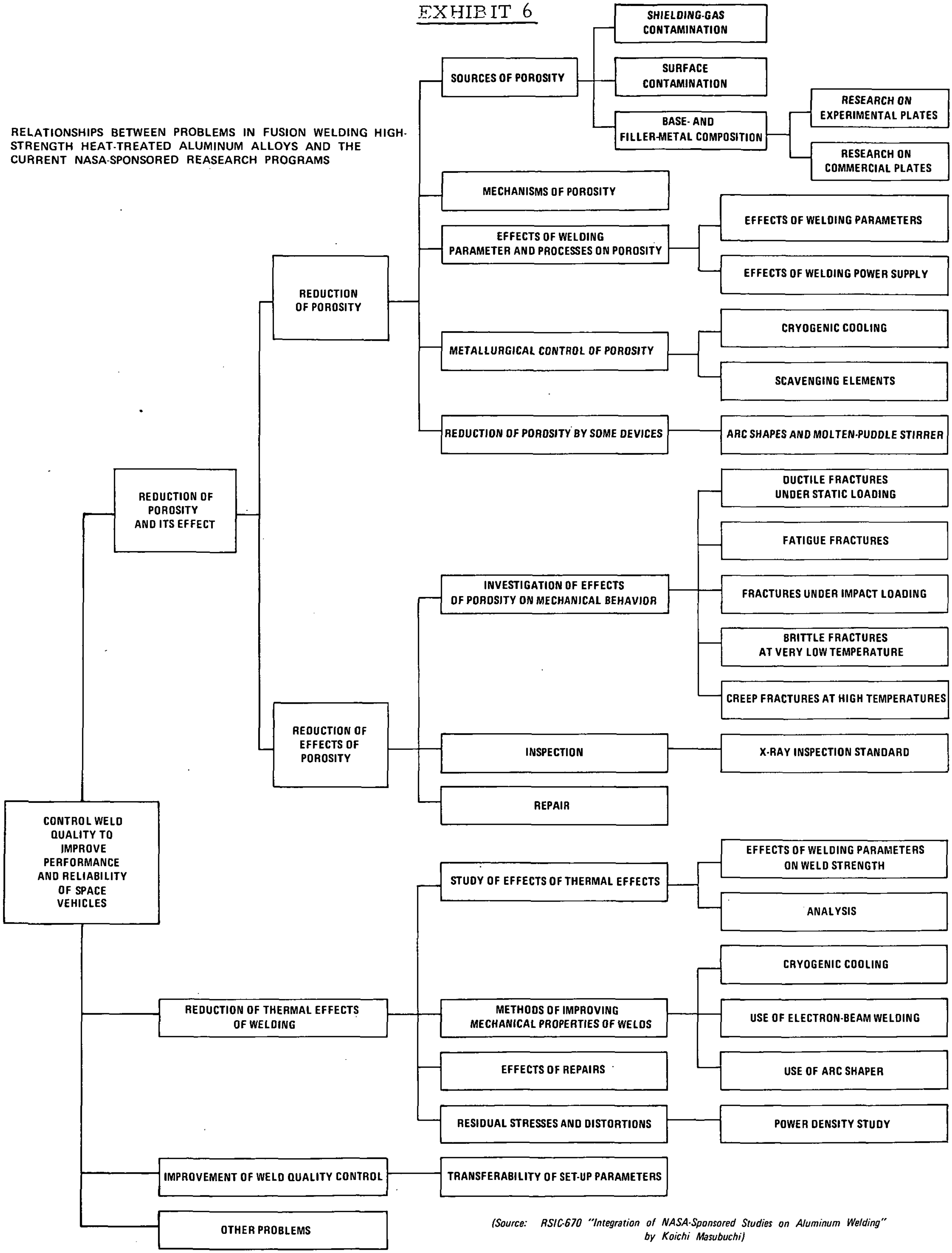
* Masubuchi, K., Integration of NASA-Sponsored Studies on Aluminum Welding, Second Edition, op. cit.

EXHIBIT 6

RELATIONSHIPS BETWEEN PROBLEMS IN FUSION WELDING HIGH-STRENGTH HEAT-TREATED ALUMINUM ALLOYS AND THE CURRENT NASA-SPONSORED REASEARCH PROGRAMS



(Source: RSIC-670 "Integration of NASA-Sponsored Studies on Aluminum Welding" by Koichi Masubuchi)

indicated a greater reduction in strength than theoretically predicted. Re-examination of the samples and further testing showed the necessity for including all pores in the measure of porosity; preliminary tests had counted only those over an arbitrary size. Subsequent studies clearly established the need for detecting porosity at very low levels. Other studies undertaken for NASA found that the fatigue strength of welded structures is also greatly reduced by porosity.

The effectiveness of repair welds was examined in order to determine how to cope with welds found to be porous, the alternatives being to repair the weld or scrap the structure. The latter option was obviously an unattractive prospect in the case of a structure the size of Saturn V's first stage. Production experience showed that 1/4 of all first repairs, 1/2 of second repairs, and 2/3 of third repairs are unacceptable. As the repeated welding with its applications of heat adversely affected the grain structure in the heat affected zone, there was a high probability that the repaired weld would exhibit poorer mechanical properties than the weld initially rejected.

The metallurgy of heat-strengthened aluminum presents particular difficulties with respect to repair welds. First, there is no adequate means of determining the actual flaw distribution or in-service strength of aluminum welds, and second, it is impossible to make truly reliable repairs. NASA's need for superior reliability in heat-strengthened aluminum welds and the cost constraints of their volume processing gave rise to the concept that very accurate process control of the initial welding operation was the most effective means of obtaining high-quality welds. It followed from this discovery that quantitative limits for welding parameters (welding speed, arc voltage, arc current, etc.) then needed to be defined for use in manufacturing specifications. This discovery of the central importance of process control constituted a conceptual breakthrough of significant dimensions. It is obviously far more cost-effective to expend resources on processes which provide basically high-quality weldments than on tests and repair techniques for raising inferior weldments to required standards.

The unacceptability, then, of the test-and-repair concept with regard to heat-strengthened aluminum alloys led to a search for means of eliminating the sources of porosity. The study focused on three aspects of pore development:

(1) Shielding gas contaminants

(2) Surface preparation of the surfaces to be joined

(3) Metallurgical characteristics of the metals to be joined and the filler metal to be used in the joint.

All of these relate to sources of hydrogen at the weld zone, hydrogen having been experimentally identified as the primary cause of porosity in aluminum welds. Although the reaction kinetics in the weld environment are not yet well understood, hydrogen is signficantly more soluble in molten than in solid aluminum. As the aluminum cools from its molten state to its solid state, outgasing of hydrogen produces tiny pores; these are what must be eliminated to achieve reliable, high-quality welds.

NASA's study of shielding gas contaminants clearly indicated the pore-producing role which these could play. Although the particular commercial gases specified by NASA were found to be sufficiently pure per se, investigations revealed that contamination can occur in partially used bottles of gas or in the distribution system from bottle to welding torch. In order to perform these experiments, sophisticated equipment was developed which monitored the shielding gas at the torch and thus assured contamination control at the welding surface. The methods developed for measuring contamination, and the discovery that the introduction of contaminants occurs after the gas bottle is opened, can find broad application in aluminum welding processes, process control, and other welding processes which are sensitive to atmospheric contamination in the vicinity of the welding operation.

Surface contamination of the metal to be welded was also found to be a major source of hydrogen at the welding site. Investigations identified the following factors as influencing the availability of hydrogen in the area of the weld:

(a) Topography of the surface

(b) Surface plastic deformation

(c) Oxide thickness

(d) Oxide crystalline structure

(e) Absorption of gases, vapors or hydrogen-bearing liquids

(f) Presence of foreign particulate matter

(g) Miscellaneous residues

Studies indicated that the best method of preparation was to machine the surfaces just prior to welding; all chemical cleaning operations were judged inferior to this mechanical removal of material.

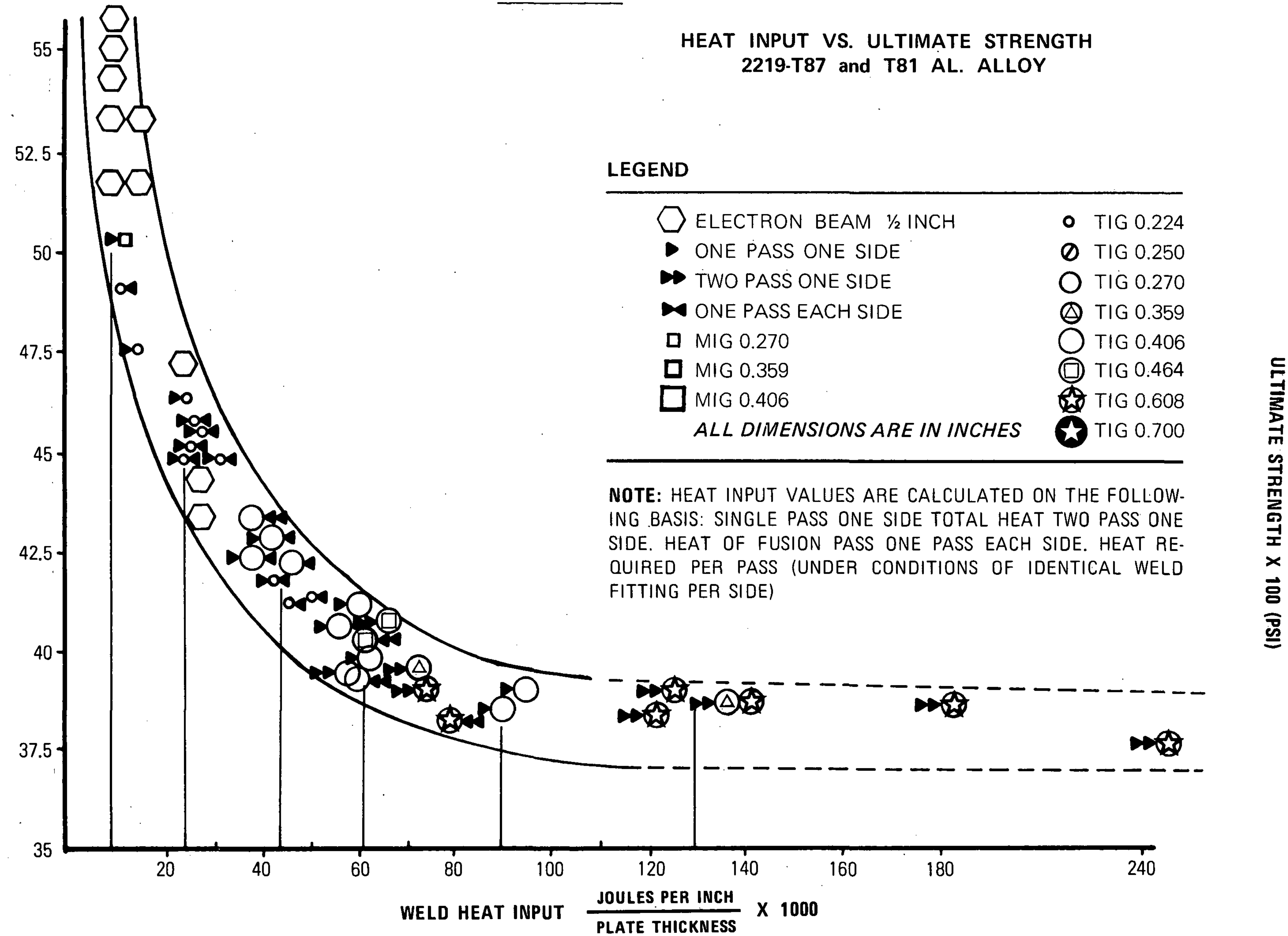
Once the surfaces have been prepared, extreme caution must be exercised to avoid re-contamination. Experiments indicated that one fingerprint contributed more than three times the level of contamination required to develop porosity in an aluminum weld, and even the use of clean gloves did not completely eliminate this source of surface contamination. Based on the results of these experiments, NASA succeeded in developing anti-contamination techniques for material preparation, set-up, and the welding operation itself. The information has since been made available to industry through NASA publications. These publications are discussed at length in Section 4. 1.

One of the most significant test instruments developed in the course of the NASA welding program was the surface contamination detector, which allows the accurate measurement of surface hydrogen. Using this tool, NASA devised a contamination index for measuring the porosity potential of various contaminants.

Since, to a large extent, investigations into the sources of porosity have complemented studies of the residual stresses and distortions induced by the welding operation, improvements effected in the overall welding process contributed to the solution of both problems.

Investigations conducted at Marshall Space Flight Center examined the relationship between the heat-affected zone and the strength of the resultant weld. The heat-affected zone is the portion of the base metal that is heated to a temperature sufficiently high to produce a metallurgical change. The Marshall study results presented in Exhibit 7 show the dramatic increase in weld strength that can be obtained by employing low heat input. The first reason for this is that heat-strengthened aluminum is adversely affected by heat above a critical temperature, and therefore the best welds are produced where very little excess energy is expended beyond that required for the fusion. Another reason why weld

EXHIBIT 7



(Source: R. V. Hoppes, The Saturn V Space Program and Aluminum Welding Technology) strength is enhanced by low energy input is that a very narrow heat-affected zone will mean that a conventional failure mode will occur partially in the unaffected parent material and not entirely in the joint.

The impressive gains achieved by reducing weld heat input clearly indicated the desired characteristics for improved welding processes. Processes capable of producing very high energy density will result in superior welds, particularly with respect to heat-strengthened materials. NASA has contributed substantial advances in this capability over what has been provided by conventional welding equipment, and has further effected improvements in the energy density characteristics of conventional equipment. Basically, as the energy input rate was lowered, porosity decreased and the mechanical and metallurgical properties improved.

The findings of this welding research program were particularly applicable in the welding of the Saturn S-IC tank structure. One portion of this structure, a dome-shaped tank enclosure 33 ft. in diameter, was initially welded by using gas tungsten arc welds. The materials joined were 0.224" thick at the joint. This initial process produced welds with unacceptably high porosity levels. Using data from the Marshall research on low-energy level welding, a gas metal arc process was chosen, which used a two-pass weld and produced excellent results on the first effort. This process allowed a more rapid deposition of weld metal and use of a lower energy density welding process than a gas tungsten arc. The use of this lower energy density process also reduced the distortion of this thin-wall aluminum structure.

The research work done in the identification of the energy input rate as a critical parameter has not ruled out certain welding processes in favor of others, but rather has allowed the selection of the correct welding process for the material being joined. The energy density characteristics of the gas tungsten process make it desirable for the welding of heavier materials (3/8" thick and above). The gas metal arc process is more suitable for the lighter materials. The electron beam welder has shown great promise for all thicknesses of material because the energy input can be carefully controlled and directed.*

*<u>Research Achievements Review Series No. 8</u>, Research and Development Operations, Huntsville, Alabama: Marshall Space Flight Center, 1965. Ref. NASA TM X-53505

The electron beam welder can produce welds of strength approaching that of heat-strengthened base metals. As the beam can be precisely controlled and focused, this welder is operational on metals of any thickness and is especially useful for heavy thicknesses. When NASA first began using the electron beam welder, the weld had to be produced in a very high vacuum, a requirement which limited its utility to small parts. To improve the versatility of the welder, NASA first funded the development of a split chamber electron beam machine, which was capable of welding larger pieces. NASA later funded the development of an out-of-vacuum electron beam welding machine, which is currently operational and producing welds of reasonable quality. This out-of-vacuum electron beam welding process may find widespread use in industry, as it is capable of much higher welding speeds, can be used on a variety of materials, and has the potential to produce quality welds.

The basic research performed at Marshall Space Flight Center on the relationship between energy input and joint strength has provided direction for the development of better welding equipment. Marshall technicians further contributed improvements to existing welding equipment and supported the development of new equipment capable of providing the required high-energy densities.

Residual Stress and Distortion

The application of extremely high welding heat and the subsequent cooling down, coupled with the thermal expansion characteristics of aluminum results in large stresses and distortions if the process is not carefully controlled. These stresses and distortions are dynamic phenomena during the welding and cooling operations, and remain as static phenomena after the welding is completed. NASA's work in the area of residual stresses and distortion has centered on developing the capability to analyze the complex stress states involved in the welding operation and find means for nondestructive evaluation of these stress states. These analytical tools and testing methods were necessary for the development of techniques and equipment to reduce the undesirable effects of localized heat in the welding process.

In order to analyze the complex mechanical behavior of stresses during and after the welding operation, computer programs were developed first at Battelle Institute and later modified and expanded at M. I. T. These computer programs, which are capable of analyzing stress distributions in welds, can provide the engineer with a basic understanding of how changes in the welding process will affect the residual stress and deformation characteristics of the welded part. The programs, as revised at M. I. T., can further analyze the dynamic stress states occurring during the welding operation which substantially determine the ultimate strength of the weld and the distortions in the finished part. These programs are applicable not only to aluminum but to the welding of any metal.

A third program is being developed to predict metal movement, the dynamic stress states, residual stresses and distortions regardless of material rigidity and heat-affected zone geometry.

Residual stresses are the tensile and compressive stresses that result from differential expansion and contraction of the welded material during heating and cooling processes. As these are present in the absence of any applied load, there is danger of structural failure should the combined force of an applied load and the residual stress equal the failure stress of the material. Thus there is a need for nondestructive measurement of residual stresses in order to determine the permissible level of applied stress. Alternatively, there is a need to control the residual stresses induced by the welding operation. Marshall Space Flight Center sponsored a study aimed at developing nondestructive methods of measuring residual stress and fatigue damage in metals. Although there exists as yet no satisfactory means for quantitative measurement, the study identified the localization of stresses at each end of a weld and provided valuable insight into the nature of residual stress states. The study also contributed to the development of ultrasonic techniques of stress determination.

The fourth area of investigation into residual stresses and distortion involved experimentally testing the concept of controlling these effects by balancing thermal stresses in the welding process. The viability of this concept was borne out in the study, and optimum patterns of thermal balance for specific weldments have been established by a combination of theoretical and empirical methods, including, notably, the use of NASA-developed computer programs.

Energy concentration is again very important when residual stresses and distortion are considered. Electron beam components are remarkably less distorted than parts welded by other processes. These electron beam welded components are similar in distortion and stress-free characteristics to the weldments produced by panels cryogenically strained during welding to control the heat patterns. Stress balancing, combined with energy concentration, should significantly reduce metal movement, distortion and porosity, and at the same time cause less material reorganization, thus providing higher strength joints. The electron beam process is most promising for these characteristics. *

Process Control

The objective of the NASA welding research program was to improve the performance and reliability of welds for space vehicles. It was determined, for reasons explained above, that this could best be achieved through careful control of the welding process. The findings of the NASA studies on weld strength, porosity, and residual stress and distortion, which were undertaken to determine the quantitative limits required for controlling the major variables of the welding operation are also useful for establishing the proper control of variable values in the manufacturing process system.

The approach taken by NASA's contractor involved the application of mathematical regression techniques to welds produced under a variety of parameter values. Six basic variables associated with gas tungsten arc welding (TIG) were identified as the weld process control parameters. These were, in order of importance:

a) travel speed,
b) electrode position,
c) arc current,
d) arc voltage,
e) gas purity, and
f) electrode tip diameter.

Other important variables such as weld joint preparation, tooling, and welding position were less quantifiable and could thus not be included among the controls.

The method employed to determine critical control parameters can be applied to any welding or joining problem. In fact, the application of regression analysis to welding variables is an extension of methods used

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Hoppes, R. V., Versatility in Electron Beam Welding, Huntsville, Alabama: George C. Marshall Space Flight Center.

in the past by engineers who selected parameters on the basis of previous experience and empirical data; for regression techniques involve quantification of past experience and integration of empirical data to identify and rank primary variables.

Research work was conducted at Marshall Space Flight Center to develop guides for automation equipment and guide followers to carry the equipment in the welding process. The guides were called tracks, and the guide followers skates. Track and skate combinations are commonly used in the precision welding of large structures such as tanks or ship hulls. NASA elaborated on this concept by developing reusable tracks fabricated of many laminites which can be easily bent into any desired shape, and a skate with individually pivoted sets of wheels, which can negotiate sharp curves on the tracks. The track and skate equipment can be used either to carry the weld preparation machining tools or to carry the actual welding gun. Further research was conducted by NASA in the development of skate systems self-regulating through the use of arc guidance and analog computers. The use of these concepts allowed NASA to develop improved process control.*

Improved process control implies in most instances the automation and mechanization of the process to be controlled. The same is true in the case of welding, where improved control is achieved by reducing the amount of human operator activity and increasing the amount of automated control. Many of the advances achieved by the Marshall program and in other NASA programs are useful in the automation of the welding process.

The individual pieces of apparatus developed for greater control of the welding process ranged from automatic filler wire feeding devices to sophisticated feedback mechanisms capable of detecting weld penetration and making necessary adjustments to travel speed and arc current to achieve the proper penetration. The following paragraphs briefly describe some of the hardware developed to improve the welding process.

An automatic reel for controlling the filler wire feed on automated welding equipment was developed to solve a production problem. Existing

*Research Achievements Review Series No. 8, op. cit.

automatic wire feed devices did not provide for take up of slack filler wire at the end of each welding operation. As a result, the wire would unwind, snarl, and foul the operation when the feed motor was restarted. The improved feed reel maintains a constant tension on the wire during the welding operation and rewinds the wire from the wire feed unit when the operation terminates. *

Automatic welding operations are frequently impaired by interference between the welding torch, filler wire feed guide and the area to be welded. Since any versatile automatic equipment must be capable of welding a diversity of shapes, it is necessary that the arrangement of the weld torch and the wire feed unit be adaptable to each situation. A universal manipulator was fabricated, which could present the weld torch and wire guide to the desired area in a semi-fixed relationship to each other and to the work. The manipulator was designed to rotate on its horizontal axis so as to avoid obstacles approaching the torch. The initial individual attitudes of the torch and wire guide are set with respect to the general configuration of the part, and minute positioning adjustments in these can be subsequently made remotely during operation. **

A closed-circuit television system was developed to meet a long-standing need for a reliable automatic arc guidance system to simplify tooling and perform remote welding. There had previously existed no technique for tracking tack-welded joints. Many complex parts are now tack-welded to align components prior to welding, and this is where an automatic arc guidance system is most useful. ***

*Millett, Alma V., <u>Automatic Reel Controls Filler Wire in Welding Machines</u>, Houston, Texas: Manned Spacecraft Center, June 1966. Tech Brief # 66-10236

**Williams, R. T., <u>Welding Torch and Wire Feed Manipulator</u>, Huntsville, Alabama: George C. Marshall Space Flight Center, October 1967. Tech Brief # 67-10385

*** Wall, W. A. Jr. and Stephans, Douglas L., <u>Closed Circuit TV System Automatically Guides Welding Arc</u>, Huntsville, Alabama: George C. Marshall Space Flight Center, September 1968. Tech Brief # 68-10357

Penetration in the welding process has usually been monitored by a human operator. A NASA-developed servo system capable of detecting variance and controlling compensatory parameters directly senses the weld properties completely from the arc side, and by means of a feedback loop to a servo mechanism, makes necessary adjustments to travel speed and welding arc current.*

Although poor welds were minimized in the fabrication of the Saturn launch vehicle, repair welding operations will occasionally be required. As the probability of defective work is higher in a repair weld than in the initial weld, it was necessary to improve the quality of repair welds and simplify repair techniques. In answer to this need, a portable machine welding head capable of automatic arc control was developed. This tool provides full automatic control of the four basic fusion type machine weld functions (arc voltage, current, wire feed, and electrode travel speed) in all welding attitudes. The equipment can make machine repairs out of position and on the side opposite the original weld.**

Two other NASA devices are discussed in Chapter 4 in connection with transfers that have occurred as a result of their development. The Tech Briefs are: Automatic Contour Welder Incorporates Speed Control System (B68-10091), Weld Quality.

3.3 Other Developments

There were many metal-joining problems in the space effort that were not associated with production of the Saturn V launch vehicle. NASA's orientation to quality, reliability and technological development produced many new devices and techniques for overcoming these other joining problems. The following paragraphs describe a number of unrelated developments which should find widespread application in the welding industry. These will be presented in the format of a problem definition, followed by a description of NASA's solution to that problem.

*McCampbell, W. M. and Cook, George, System Maintains Constant Penetration During Fusion Welding, Huntsville, Alabama: George C. Marshall Space Flight Center, April 1967.
Tech Brief # 67-10091

**Robb, M. A. and Oleksiak, C. E., Portable Machine Welding Head Automatically Controls Arc, Huntsville, Alabama: Marshall Space Flight Center, August 1967.
Tech Brief # 67-10272

Large diameter pipes or tubing which are to be joined by welding require preparation of the mating surfaces prior to joining. This is normally accomplished by hand filing, torch cutting, or grinding or machining. Conventional field equipment is generally cumbersome or imprecise, and the use of shop preparation processes is expensive and time consuming. To overcome this problem NASA developed an improved scarfing tool consisting of a mountable roller-guided assembly which can convert a conventional routing machine for relatively precise field preparation of pipes for welding. The tool is inexpensive, very portable, and designed for operation by personnel with a minimum of training and skill.*

There was a need for a table or platform for the flame cutting of metal of various types, shapes and thicknesses, which would not be damaged by the torch cutting operation. A 10 foot square welding table was greatly improved when covered by parallel, inverted ten foot long steel angles. Small x-section riders were then made to mate the angles forming the cutting table. These x-sectioned riders can be positioned to support the material to be cut in any desired fashion. Cutting the material damages very few riders, and these can be cheaply replaced as they are usually made up from scrap pieces of angle.**

A novel and functional clamping concept was developed for the positioning of parts of the large rocket components. The clamps allowed for proper alignment without the use of back-up bars. The clamps are composed of two metal blocks connected by a thin stainless steel bank one inch wide. A slot is cut into the materials to be joined so that the band can pass through the materials. A pin on the inside clamp holds the band and there is a take-up spool; the blocks are drawn together, and the materials to be joined are aligned between the blocks. During the welding operation, the clamps are released one at a time approximately six inches in front of the weld.***

*Wallace, Elvis D., Weld Preparation Tool for Pipes and Tubing, Kennedy Space Center, Florida: Kennedy Space Center, December 1967. Tech Brief # 68-10551

**Oliver, D. H., and Ramirez, M., Improved Table for Cutting and Welding, Houston, Texas: Manned Spacecraft Center, September 1969. Tech Brief # 69-10346

***Franklin, W. J. and Martin, N. C., Novel Clamps Align Large Rocket Cases, Eliminate Back-Up Bars, Huntsville, Alabama: Marshall Space Flight Center, January 1964. Tech Brief # 63-10376

Another problem in the alignment of materials to be joined is the application of a specified clamping pressure to hold materials together during the joining operation. To achieve the specified force, a spring-loaded clamp with adjustable legs terminating in suction cups was developed for NASA. The suction cups allowed the attachment of this device to any level surfaces, and the spring-loaded clamp with the calibrated adjusting screw permitted the application of desired pressure.*

NASA also confronted the problem associated with conventional welding of maintaining a hand-held spot welding gun in steady contact with the work piece. Involuntary lateral movements and unsteady pressure of the gun nozzle on the work piece tend to produce cracks and deformities in the spot welds. To solve this, a shoulder adapter was made to fit one end of the gun. The adapter, about 15-20 inches long, is made of lightweight metal; one end of the adapter is recessed to fit snugly over the gun stock, and the other end is made to fit the shoulder of the welder. This adapter permits the operator to hold the gun steadily at uniform pressure against the work piece, thus expediting the welding process and facilitating defect-free welds.**

A miniature tungsten insert gas welding torch developed for NASA can be used with variously formed, interchangeable soft copper tubing extensions. This provides an inexpensive and accurate welding capability for inaccessible or hard-to-reach joints. The extensions can be manipulated to position the welding head around obstructions. The soft copper can be formed to smaller radii than was possible with previously used TIG torches, and it retains its shape. The low-cost extension heads can be shaped to fit any particular joint that is to be welded.***

In a welding program conducted at Lewis Research Center, refractory metals, alloys of such metals as zirconium, titanium columbium, and tantalum were joined by welding. In the research studies, commercially available manual

* Calibrated Clamp Facilitates Pressure Application, Houston, Texas: Manned Spacecraft Center, February 1966.
Tech Brief # 66-10059

** Love, T. H., Shoulder Adapter Steadies Spot Welding Gun, Huntsville, Alabama, Marshall Space Flight Center, March 1966.
Tech Brief # 66-10076

*** Stein, J. A., Torch Kit for Welding in Difficult Areas, Houston, Texas: Manned Spacecraft Center, April 1971.
Tech Brief # 71-10070

welding torches were found to introduce undesirable contamination to the weld atmosphere. To solve this problem, a specially designed welding torch was developed, composed of tooling so impermeable as to result in practically zero contamination to the weld environment. * This torch is but one of the results of a study that will certainly contribute to the improved welding and greater usefulness of refractory metals.

Another improved welding gun was developed for NASA to facilitate spot welding in confined areas. It was necessary to provide a simple and inexpensive apparatus for touch-starting a power arc using a consumable electrode. The device had to be sufficiently small and light to be hand-held during the welding operation. The solution was a power arc welder in the form of a hand-held welding gun which touch starts, automatically retracts a consumable electrode a distance sufficient to create the desired arc, and then commences feeding of the consumable electrode at the rate required to form the intended bead or spot. **

Machining and welding in confined or hard-to-reach areas is always difficult and sometimes impossible. This is a problem frequently encountered in industry, and one which constantly plagued NASA in the early stages of the welding program. To improve this situation, a flexible drive was developed for NASA, which allows blind machining and welding in such areas. The machine or welding head is connected to the control or power unit by a flexible transmission shaft and incorporates a locking indexing collar into the machine or welding head to allow the head to be placed and held in position. The flexible transmission shaft is inside a neoprene extrusion that contains three lengthwise passages for carrying gas and electrical power to the head and the bi-directional flexible shaft. ***

* Lessman, G. G. and Sprecace, R., Improved Torch Increases Weld Quality in Refractory Metals, Cleveland, Ohio: Lewis Research Center, Feb. 1968.
Tech Brief # 68-10041

** Jeannette, Joseph C., Power Arc Welder Touch-Started with Consumable Electrode, Huntsville, Alabama: Marshall Space Flight Center, December 1966.
Tech Brief # 66-10641

*** Rohrberg, R. G. and Harvey, D. E., Flexible Welding and Milling Equipment, Houston, Texas; Manned Spacecraft Center. Supplement to Tech Brief # 66-10428.

An ultrasonic hand tool was developed for NASA to scan spot welds for defects. Previous ultrasonic techniques did not allow convenient scanning of areas inaccessible to bulky test equipment. The device produced for NASA was an electrically powered hand tool which, coupled with auxiliary ultrasonic equipment, can readily scan small areas for defects in spot welds.*

Another lightweight portable instrument developed for the non-destructive inspection of welds was an ultrasonic recording scanner. The scanner employs two point beam ultrasonic transducers mounted in a V configuration so that the ultrasonic beams intersect at a common point on the test surface. One transducer transmits the ultrasonic signal, and the other receives it reflected from the test surface. A chart records a solid line where the weld is continuous and a broken line where weld discontinuities occur. The result is a simple, direct reading record of the weld quality, requiring no further processing or transcription of the data.**

Distortions caused by the residual stresses induced in the welding process are often unacceptable in the finished structure. Time consuming hammer and die operations commonly used for removing these distortions are not generally reliable and tend to damage the surface finish of the materials processed. To solve this problem, a portable, electromagnetic hammer was developed by NASA. In this hammer, a coil generates a controlled high energy pulse magnetic field over localized areas on the metal surface. The magnetic field applies a fairly uniform force over an area corresponding to that of the face of the coil. This force removes distortions by bending or stretching the affected metal without the use of a die.***

Three other NASA developments are discussed in Chapter 4 with regard to the transfers that have occurred as a result of their invention. The Tech Briefs involved are: Inert-Gas Welding and Brazing Enclosure Fabricated From Sheet Plastic (B65-10338), Camera Lens Adapter Magnifies Image (B67-10431), and a Biaxial Weld Strength Prediction Method (B69-10471).

* Mitchell, D. K., <u>Ultrasonic Hand Tool Allows Convenient Scanning of Spot Welds</u>, Huntsville, Alabama: Marshall Space Flight Center, July 1966.
Tech Brief # 66-10289

**<u>Ultrasonic Recording Scanner Used for Nondestructive Weld Inspection</u>, The Boeing Company under contract to Marshall Space Flight Center, Huntsville, Alabama, May 1966.
Tech Brief # 66-10220

*** Schwinghamer, R. J., <u>Electromagnetic Hammer Removes Weld Distortions from Aluminum Tanks</u>, Huntsville, Alabama: Marshall Space Flight Center, November 1965.
Tech Brief # 65-10342

Summary

NASA undertook a comprehensive and carefully structured program to solve the problems encountered in welding heat-strengthened aluminum structures. Initial development of a rational investigative framework allowed work to progress in an orderly, efficient manner with minimal duplication of research effort. The field of welding as a whole has profited greatly from NASA's contributions in testing techniques, new equipment and equipment concepts, and methods of weld preparation and accomplishment. Furthermore, the framework itself provides valuable direction for future welding research.

NASA has made significant contributions to the welding industry. Many of the contributions are quite subtle, beyond the reach of symbolism and often never recognized. It is, perhaps, the results of their welding efforts which best display the important advances provided by NASA from which industry can benefit. On the last S-II Saturn launch vehicle, 24,123 inches of finished weld bead were produced, and only 1/2 inch of rework was required.* The last twelve vehicles were processed with only 100 inches of rework on a total requirement of four and one-half miles of finished weld bead. This record was achieved while producing welds with strength 28% higher than the industry average less than ten years before. NASA's attainment of more reliable and higher quality welds was accomplished through the application of sound scientific and engineering practices. In some cases the specific developments may be directly transferable; but in more general terms, NASA has clearly demonstrated the cost reduction and improved quality that are possible, and which are attainable by industry through use of the same techniques.

*"Saturn V - 99.998% welding perfection achieved", in Quality Assurance, February 1971.

4.0 NASA WELDING TRANSFER EXAMPLES

The most significant transfers that have taken place in the field of welding are also the ones which are most difficult to pinpoint and specify. As a result of the requirements of the space program, NASA has funded a great deal of research and development in numerous welding industries. This funding has resulted in advanced knowledge of welding procedures and has contributed to the successful development of advanced welding equipment. However it is very difficult to isolate the transfers, because most of the transfers are in the form of knowledge or ideas. Typically, a firm which has done welding contract work for NASA is later able to use some of the concepts or procedures for its welding equipment design or welding applications.

The evolution of electron beam welding is a prime example. NASA funding helped to make the commercial use of EB welding a reality. Without the development funding that NASA provided, widespread practical use of electron beam welding would probably be much farther off in the future than it is now. Job shops which formerly performed EB welding for aerospace and nuclear applications now devote a substantial fraction of their time to industrial work.[*] There is no one technique or piece of equipment which can be claimed as a panacea. However the general expertise gained as a result of NASA's funding has had a substantial influence on welding job shops. A number of the transfers have occurred through individuals. Many welding engineers who worked under NASA funded research later joined job shops and brought with them a wealth of information. Unfortunately few people recognize the real importance of such a transfer.

The manager of general administration of a well known welding company has been quoted as saying:[**]

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[*] Ronald Khol, "Electron-Beam Welding," Machine Design, October 15, 1970, page 137.

[**] Mr. A. L. Sciaky as quoted by K. W. Bennett, "Space Program Boosts Welding Techniques," The Iron Age, October 10, 1968, page 55.

"The state-of-the-art in welding was advanced 20 to 25 years as a result of this (Saturn-Apollo moon shot) program. TIG-spot welding in the auto industry today is an offspring of this and would still be 15 years away but for this space research.

Most welding in the space program is TIG/MIG and this is the area of great technological gains. There's just been an awful lot of fallout for the metalworking world."

This chapter is devoted to the presentation of a number of transfer examples which are specific enough to have been documented. The examples cover a wide variety of welding aspects -- from welding procedures and standards, to test equipment and accessories.

4.1 Welding Techniques and Procedures

NASA has done a great deal in the way of setting up procedures and standards for welding. A manual entitled "Workmanship Manual For Welding"*, prepared jointly by NASA and the AEC, has had widespread use throughout industry. The manual describes and defines the quality and workmanship standards which are required for the fabrication by fusion welding of components, piping, assemblies and systems for the NERVA program at the Nuclear Rocket Development Station. The document covers numerous aspects of fusion welding such as basic rules and qualifications, shielding gas, care of filler material, weld identification, root pass, filler pass, face pass, and socket welds. The manual includes written descriptions and pictorial presentations of various types of welds and their preparation. Photographs of acceptable and unacceptable welds are also featured. In addition to the normal announcements made of the manual, both Science Trends and The Machinist publicized it.

The Hazeltine Corporation incorporated portions of the manual into a revision of their own Workman Quality Handbook. The Hazeltine Corporation produces radar systems and felt that the information used from the NASA-AEC

*M. D. Phillips, NTO-SOP-0090, NERVA Test Operations, Jackass Flats, Nevada, October, 1966.

manual would help maintain their rigid requirements. Production and inspection personnel use the completed manual. A quality assurance engineer at Hazeltine felt that the manual had helped improve production efficiency and saved development time and money.

Engineers who are responsible for the maintenance of certain processing equipment at the Foremost Food Company were unhappy with the amount of corrosion of equipment welds. The engineers used the NASA-AEC manual in addition to a study of welding specifications for their equipment. The manual helped provide the answers to several technical questions and the engineers were able to solve the corrosion problem. Although the monetary savings could not be estimated, the chief engineer stated that they were signficant.

A Pennsylvania engineer who was working with a consulting firm was confronted with a quality control problem in connection with a small construction firm doing work on the Foster Joseph Sayers Dam. The firm faced a cost overrun and had trouble meeting the welding qualifications requirement. The NASA-AEC manual was very useful in checking the welding procedures and in helping to qualify personnel. Partially through the use of the manual, the firm was granted a change and allowed to use T-1 steel. This change resulted in substantial savings on the construction costs of the dam.

In three separate cases, the Workmanship Manual for Welding has been used for educational programs. The Raytheon Company used it as a reference for their training program in order to familiarize the weld inspector trainees with the characteristics of good quality welds.

Taylor Forge, Inc. has used the manual as reference material in welding and weld inspection training programs. The manual has been used mostly for preparing training course material and orientation for novice personnel.

The M. W. Kellogg Company uses the NASA-AEC manual as a primary reference for its educational program to upgrade the welding knowledge of its employees and to increase their professional competence by in-service training. The company is also using the manual to support its efforts to raise the standards of the present welding codes.

A large New England manufacturer of transformers purchased a semi-automatic welding system after having performed a cost analysis and demonstrating the effectiveness of the proposed modifications. The welding engineer who performed the cost study derived a substantial portion of the information he used from the NASA-AEC manual. The adoption of the automatic equipment has increased efficiency and the company plans to examine the use of additional automated equipment. The engineer has estimated that the changes will result in a savings of as much as $500,000 over a period of 4 years.

The Workmanship Manual is also being used by the California Division of Highways as input for a welding manual. The manual is used as a guide for state employed welding inspectors in their work with ultrasonic equipment.

Finally there have been many cases of the manual's use to update knowledge of the state-of-the-art in welding technology. Many individuals have felt that the manual has helped to improve their technical skills. Persons at the following companies are a few who have found the document helpful: Water Resources Department, State of California; Sperry-Rand Corporation; Hewlett Packard Company; McGraw-Edison Company; and Stephens-Adamson Manufacturing Company.

Design of aerospace and other structures is usually based upon the mechanical properties of the material used for construction. The strengths are usually obtained from simple coupon tests under uniaxial loading. However, many structures, such as pressurized liquid propellant tanks, do not undergo simple uniaxial loads. Instead such structures experience multi-axial loading due to the existing internal pressure. Since yield strength and ultimate strength of metal alloys can differ depending on whether the properties are measured in uniaxial or biaxial tension, it can be advantageous to use biaxial mechanical properties in designing these tanks. This is particularly true in cases where weight-saving is important, since the use of higher biaxial strengths in design results in lighter structures than when uniaxial strengths are used. Normally, predicting biaxial strengths is not a problem; however, in the case of aluminum alloys in which the mechanical properties of the welds differ from those of the parent metal, the standard formulas cannot be applied.

A NASA Tech Brief* and Technical Support Package describe a modified uniaxial formula which can be used to determine biaxial strengths for large tanks. The method has not only been valuable for the design of NASA's large propellant tanks, but has found an important use at the Eastman Kodak Company in Tennessee. The plant was having problems in its manufacturing processes which used pipes carrying chemicals. The pipes occasionally failed along the lateral weld under a pressure surge, creating a serious safety hazard. The problem was solved after the pipes were redesigned using the weld strength prediction method. As a result there has been a signficant improvement in plant safety with relatively little time and expense. The Kodak engineers will continue to apply the prediction method as the need arises to improve pipes used in other parts of the manufacturing process.

Professor C. A. Ellsworth of Industrial Engineering at the Pennsylvania State University regularly obtains Tech Briefs for use as background material in his courses on welding. One of these is a welding familiarization course for sophomores with 75 to 100 students attending each academic year. A second more advanced course is for juniors from both the College of Engineering and the Department of Materials Sciences. The junior level course normally is taught to about 10 students during the academic year. Professor Ellsworth stated that the Tech Briefs help generate new ideas for lectures and help to keep him up to date on new welding techniques. He observed that the NASA information was helping to fill a void in the literature since the documents frequently discuss the use of new techniques and unusual materials. Examples of the Tech Briefs he has used are: Effect of Welding Position on Porosity Formation in Aluminum Alloy Welds (67-10177), Opposed Arcs Permit Deep Weld Penetration with Only One Pass (66-10513), and Welds Chilled by Liquid Coolant Manifold (66-10354).

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*B69-10471, A Biaxial Weld Strength Prediction Method.

4.2 Weld Test and Inspection Equipment

In addition to establishing rigid welding standards and procedures, NASA has also required the development of testing techniques and equipment in order to assure that high quality welds are actually attained. Researchers at the Marshall Space Flight Center have been responsible for the development of a Mechanized Ultrasonic Scanning System,* designed to inspect the flaw content in the welds of space vehicle booster stages and propellant tanks. The system was capable of scanning welds at speeds greater than 1 inch per second. The most significant achievement of the system was the development of a water column probe which eliminates the necessity of submerging the weld under test in water or providing a water flush over the weld surface. Although X-ray techniques have been used for some time to test butt welds, the range of material thicknesses used in space vehicles components limited the capability of X-rays in detecting lack-of-fusion and lack-of-penetration defects. The ultrasonic scanning system provides a higher degree of reliability in the detection of flaws.

The F. Yeager Bridge and Culvert Company is planning to use the ultrasonic scanning system as soon as better techniques are developed for interpreting the test results. The company builds steel bridges for the Michigan Highway Department. The company president is anxious to replace currently used X-ray inspection techniques with the ultrasonic device for its considerable cost savings. He reported that the system components could be purchased for about $7,000 and, at that price, the system would pay for itself in six months and would result in a sizable savings over a longer period. The company is also interested in the portability and recording features of the equipment.

Engineers at DeLaval Turbine, Inc. have evaluated the ultrasonic system and will probably adopt it as soon as a suitable method for interpreting the test results is developed. The company would use the device

*Tech Brief 68-10004.

in quality control testing of the compressor wheels which it produces. A company spokesman stated that the system is a potentially more efficient technique for their quality control testing than the methods they presently use such as X-ray.

A new device called the Infrared Weld Evaluator has been developed under a NASA contract.* The instrument automatically and nondestructively monitors the quality of welds produced during micro-resistance welding of electronic assemblies. It automatically measures the infrared energy generated in the weld during weld formation on each workpiece and compares the energy with the allowed range of infrared energy values previously determined through correlation with 17,000 acceptable and unacceptable welds made at various energy levels. If the infrared energy measured is not within the allowable range, a red indicator light turns on and the monitor turns off the welding system power supply so that the fault can be corrected before any further welding is performed. The device ensures 100 percent nondestructive inspection of the welds on every workpiece. This constrasts strongly with present systems which destructively or nondestructively perform tests on a few samples after welding has been completed.

After reviewing the Technical Support Package, a manufacturer of integrated circuit bodies which require considerable resistance wiring has decided to replace its present destructive-sampling quality control methods with a 100 percent nondestructive inspection method. The manufacturer is presently trying to obtain a commercial system similar to NASA's and hopes to install 30 instruments. This system change is expected to reduce production costs by $25,000 in the first year in addition to ensuring a more reliable product. The manufacturer was led to this decision after examining the NASA literature.

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*Tech Brief B68-10333.

A researcher at the Marshall Space Flight Center has developed an efficient method for photographing weld flaws.* During the examination of welds for possible flaws, such as discontinuities or cracks, those which are not visible without the aid of a magnifying glass must be photographed and the pictures enlarged to bring out any flaw detail. This procedure is very time-consuming and expensive. The NASA researcher adapted an illuminated 7-power magnifier to a standard Poloroid Land Camera. The magnifying lens and light are mounted on a depth adjustable support bracket. A nondestructive testing consultant for Mobil Research and Development Corporation has found the idea to be extremely useful. He had the company's machine shop fabricate a similar device and he has used it a number of times for weld inspection. The device supplements his other testing equipment and provides a permanent record of visible weld flaws.

4.3 Welding Equipment Design

A NASA researcher has designed a speed control system which maintains the welding torch of an automatic welder at a substantially constant speed.** The system is especially useful for welding contoured or unusually shaped surfaces, where the distance from the weld carriage to the work surface varies randomly.

The system utilizes a speed pickup wheel to monitor the speed of the welding torch carriage. The speed of the wheel is converted into a smooth voltage output using a rate generator. This voltage is compared to a reference voltage and the difference is used to correct the speed of the weld carriage drive motor if the speed is not as desired.

The Cecil Equipment Company carefully examined the NASA system and has decided to incorporate a slightly modified version into an existing product, an automatic guidance system. The NASA device represented a capability not available in the Cecil's equipment and will improve the quality of the resulting welds. The types of customers

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*Tech Brief B67-10431, Camera Lens Adapter Magnifies Image.

**Tech Brief B68-10091, Automatic Contour Welder Incorporates Speed Control System.

interested in this capability include automobile plants, bridge and iron contractors, manufacturers of nuclear vessels, certain construction contractors, and manufacturers of dome welding.

September 1972 is the completion date set for the Cecil system. There is a large market for this type of equipment and Mr. Shelby Cecil estimates that during the next five years, sales of their new automatic equipment will be over $1 million. Mr. Cecil believes that the automatic device "will become a very important component in the welding industry."

For a number of years the Westinghouse Electric Corporation has been working on the development of an out-of-vacuum electron beam welder. NASA has been very interested in a device of this type and granted Westinghouse an equipment contract to develop one of the first machines. NASA has used the device successfully and, since the initial construction, has had the machine rebuilt to new specifications. According to a Westinghouse spokesman who is presently responsible for managing the sales of out-of-vacuum electron beam welders, the NASA equipment contract was a valuable step in bringing the welder to commercialization. Had it not been for NASA's funding, the Westinghouse device very likely would not have reached the market in its present state as early as it has. It is difficult to estimate the market size at this time but it appears that the new welder could prove valuable in numerous industries.

4.4 Welding Accessories

NASA has devised a number of welding equipment accessories such as automatic wire feed controls, weld cooling manifolds, clamps for aligning structures to be joined, and weld preparation tools. These accessories are often simple in nature, but they add substantially to the efficiency of the welding process. One such novel device is an inert gas welding chamber made from sheet plastic.* Previous to

*Tech Brief B65-10338, Inert-Gas Welding and Brazing Enclosure Fabricated from Sheet Plastic.

this concept, expensive inert gas chambers were used. Such a chamber is a necessity for welding metals which are affected by the normal gases contained in the air. As contamination by air during welding frequently causes cracks, porosity and loss of ductility for certain metals, an inert gas atmosphere is often required.

Problems occurred with the standard chambers not only because of their expense but also because the chambers did not accommodate large pieces of equipment and were difficult to use when the workpiece was attached to some fixed equipment such as pipelines. The plastic chamber can be inexpensively custom-fabricated around the portion of the equipment to be welded. The seams are taped and provisions made for a rigid window and the attachment of inert gas and vacuum pipelines. Rubber gloves extending into the chamber are installed and sealed.

The Communications Satellite Corporation has found the plastic enclosure to be a valuable technique. Construction of several different size enclosures made possible the fabrication of parts that would be difficult to make otherwise. The company uses the chambers for welding structural antennas and antenna parts made of titanium, which must be welded in an inert atmosphere in order to assure reliability.

The company has constructed several different size enclosures for convenience. Each of these costs less than $100. Without this type of chamber, a welding table would have been required. A single table costs between $1,200 and $3,000.

A New England company expects to market within one year plastic chambers based on the design of NASA enclosures. This chamber will be an accessory device for a new line of special plasma welding equipment. A company vice president has estimated that the availability of this concept will save his company close to one man-year of effort. The company will charge on the order of $1,000 for the plastic chamber as opposed to $3,000-$10,000 for the conventional metal enclosures. The chamber is superior not only because of its low cost but also because it is portable and provides better visibility. The firm will market one size enclosure at first but will probably extend its line to several sizes later on.

APPENDIX

Welding Tech Briefs and the Number of Requestors for Technical Support Packages

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
	TECHNIQUES AND PROCEDURES	2,513 TOTAL
63-10139	Method of Welding Joint in Closed Vessel Improves Quality of Seam	2
64-10309	Welding Procedure Improves Quality of Welds Offers Other Advantages	2
65-10319	Refractory Metals Welded or Brazed With Tungsten Inert Gas Equipment	69
66-10125	Aluminum Oxide Filler Prevents Obstructions in Tubing During Welding	53
66-10458	Heat Treatment Stabilizes Welded Aluminum Jigs and Tool Structures	83
66-10513	Opposed Arcs Permit Deep Weld Penetration with Only One Pass	16
67-10069	Controlled Ferrite Content Improves Weldability of Corrosion-Resistant Steel	69
67-10177	Effect of Welding Position on Porosity Formation in Aluminum Alloy Welds	103
67-10183	Continuous Internal Channels Formed in Aluminum Fusion Welds	26
67-10195	Weld Procedure Produces Quality Welds for Thick Sections of Hastelloy - X	47
67-10200	Workmanship Standards for Fusion Welding	1,607
67-10232	Welding, Bonding, and Sealing of Refractory Metals by Vapor Deposition	42
67-10292	Welding of AM350 and AM355 Steel	4
67-10392	Study Made of Ductility Limitations of Aluminum - Silicon Alloys	14
67-10464	Tube-To-Header Joint for Bimetallic Construction	4
68-10310	Standards for Compatibility of Printed Circuit and Component Lead Materials	142

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
68-10383	Effects of High Frequency Current in Welding Aluminum Alloy 60601	60
68-10561	Weld Joint Strength and Mechanical Properties in 2219-&81 Aluminum Alloy	3
69-10052	Hot-Cracking Studies of Inconel 718 Weld Heat-Affected Zones	18
69-10085	Tube Welding and Brazing	31
69-10086	Techniques for Controlling Warpage and Residual Stresses in Welded Structures	10
69-10145	Mixing Weld Gases Offers Advantages	22
69-10150	Renewal of Corrosion Protection of Coated Aluminum After Welding	4
69-10264	Welding, Brazing, and Soldering Handbook	24
69-10302	Parameters for Good Welding of Copper to Nickel	7
69-10303	Quality-Weld Parameters for Microwelding Techniques and Equipment	12
69-10372	Effects of Hydrogen on Metals	5
69-10404	Generation of Sonic Power During Welding	21
69-10471	A Biaxial Weld Strength Prediction Method	8
70-10127	Improved Electron-Beam Welding Technique	4
70-10412	Improved Electron Beam Welding Technique	1
	WELD PREPARATION	269 TOTAL
64-10164	Upsetting Butt Edge Increases Weld-Joint Strength	
66-10145	Portable Power Tool Machines Weld Joints in Field	31
66-10248	Electrical Upsetting of Metal Sheet Forms Weld Edge	
68-10285	Pre-Weld Heat Treatment Improves Welds in Rene 41	66
68-10302	Effects of Surface Preparation on Quality of Aluminum Alloy Weldments	18

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
68-10551	Weld Preparation Tool for Pipes and Tubing	1
69-10051	Welded Repairs of Punctured Thin-Walled Aluminum Pressure Vessels	3
69-10229	J-Beveling of Pipe Ends with a Hand-Held Tool	86
69-10231	Tool Simplifies Machining of Pipe Ends for Precision Welding	63
69-10305	Repair of Weld Defects in Thin-Walled Stainless Steel Tubes	1
		259 TOTAL
	WELDING EQUIPMENT	
65-10401	Photosensors Used to Maintain Welding Electrode-to-Joint Alignment	2
66-10357	Suppressor Plate Eliminates Undesired Arcing During Electron Beam Welding	4
66-10441	Standard Arc Welders Provide High Amperage Direct Current Source	1
66-10641	Power Arc Welder Touch-Started with Consumable Electrode	61
67-10091	System Maintains Constant Penetration During Fusion Welding	57
67-10272	Portable Machine Welding Head Automatically Controls Arc	2
67-10385	Welding Torch and Wire Feed Manipulator	5
68-10091	Automatic Contour Welder Incorporates Speed Control System	36
68-10332	Dual Wire Weld Feed Proportioner	14
68-10566	Welding Skate with Computerized Controls	4
69-10393	Conversion of Continuous-Direct-Current TIG Welder to Pulse-Arc Operation	58
70-10136	Butt Welder for Fine Gage Wire	15

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
	WELDING ACCESSORIES	893 TOTAL
63-10240	Sleeve and Cutter Simplify Disconnecting Welded Joint in Tubing	
63-10384	Vacuum-Type Backup Bar Speeds Weld Repairs	
65-10338	Inert-Gas Welding and Brazing Enclosures Fabricated From Sheet Plastic	65
65-10342	Electromagnetic Hammer Removes Weld Distortions from Aluminum Tanks	7
66-10059	Calibrated Clamp Facilitates Pressure Application	28
66-10076	Shoulder Adapter Steadies Spot Welding Gun	25
66-10092	Fingertip Current Control Facilitates Use of Arc Welding Gun	1
66-10093	Tool Provides Constant Purge During Tube Welding	58
66-10153	Argon Purge Gas Cooled by Chill Box	
66-10155	Simple Device Facilitates Inert-Gas Welding of Tubes	36
66-10215	Electron Beam Welding of Copper-Monel Facilitated by Circular Magnetic Shields	1
66-10236	Automatic Reel Controls Filler Wire in Welding Machines	88
66-10323	Special Mandrel Permits Uniform Welding of Out-of-Round Tubing	71
66-10354	Welds Chilled by Liquid Coolant Manifold	95
66-10428	Flexible Drive Allows Blind Machining and Welding in Hard-to-Reach Areas	60
66-10443	New Backup-Bar Groove Configuration Improves Heliarc Welding of 2014-T6 Aluminum	114
67-10107	Composite Weld Rod Corrects Individual Filler Weaknesses	35

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
67-10162	Closed Circuit TV System Monitors Welding Operations	14
67-10326	Portable Spectrometer Monitors Inert Gas Shield in Welding Process	2
67-10373	Eccentric Drive Mechanism is Adjustable During Operation	
67-10472	Aluminum and Stainless Steel Tubes Joined by Simple Ring and Welding Process	15
68-10022	Mechanical Shielding Reduces Weld Surface Cracking in 6061 TG Aluminum	16
68-10041	Improved Torch Increases Weld Quality in Refractory Metals	14
68-10242	Welder Analyzer	70
68-10357	Closed Circuit TV System Automatically Guides Welding Arc	43
69-10164	Detachable Caster Adapter	
69-10346	Improved Table for Cutting and Welding	
69-10396	Quick-Acting Backup Tool for Welding Ducts	5
69-10533	Gas Metal Arc (GMC) Weld Torch Proximity Control	24
70-10041	Spinarc Gas Tungsten Arc Torch Holder	
70-10044	Modified Faceplate Assembly for Stud-Welding Gun	
70-10604	Filler-Wire Positioner for Electron Beam Welding	6
71-10070	Torch Kit for Welding in Difficult Areas	
	APPLICATIONS	270 TOTAL
63-10367	Connector for Vacuum-Jacketed Lines Cuts Tubing System Cost	
63-10368	Composite, Vacuum-Jacketed Tubing Replaces Bellows in Cryogenic Systems	

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
63-10385	Flexible Honeycomb Structure Can Bend to Fit Compound Curves	
65-10220	Thoriated Nickel Bonded by Solid-State Diffusion Method	1
65-10309	Thermoelectric Elements Diffusion-Bonded to Tungsten Electrodes	2
66-10020	O-Ring Tube Fittings Form Leakproof Seal in Hydraulic Systems	
66-10247	Pressure-Welded Flange Assembly Provides Leaktight Seal at Reduced Bolt Loads	
66-10250	Diffusion Bonding Makes Strong Seal at Flanged Connector	
66-10365	Diaphragm Valve for Corrosive and High Temperature Fluid Flow Control Has Unique Features	4
66-10445	Weldable Aluminum Alloy Has Improved Mechanical Properties	2
66-10464	Large Seals Fabricated from Small Segments Reduce Procurement Lead Time	18
66-10582	Composite Bulkhead Fabrication Development	1
66-10613	New Weldable High Strength Aluminum Alloy Developed for Cryogenic Service	54
67-10163	Effects of Heat Input Rates on T-1 and T-1A Steel Welds	63
67-10436	Fuel Cell Life Improved by Metallic Sinter Activation After Electrode Assembly Welding	4
68-10063	Plastic Preforms Facilitate Fabrication of Welded Cordwood Electronic Modules	8
68-10192	Welding of Commercial Base Plates is Investigated	7
68-10251	Weld Microfissuring in Inconel 718 Minimized by Minor Elements	35
68-10307	Encapsulation Technique Eliminates Thermal Stresses in Welded Electronic Modules	14

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
68-10331	Electron Beam Selectively Seals Porous Metal Filters	15
69-10237	Diffusion Bond Method of Joining Steel and a TFE-Bronze Composite	3
69-10261	Repair of Honeycomb Panels with Welded Breakaway Studs	
69-10403	Pressure-Control Purge Panel for Automatic Butt Welding	1
69-10544	Rhodium-Plated Barrier Against High-Temperature Fusion Bonding	23
69-10601	Cryogenic Pressure Transducer	
70-10155	Applications of Gap Welding	9
70-10331	Fabrication of Hollow Ball Bearings by Diffusion Welding	3
70-10367	Improved Welding of Rene-41	3
	WELD TEST AND INSPECTION	967 TOTAL
65-10110	Magnets Position X-Ray Film for Weld Inspection	3
65-10111	Probe Tests Microweld Strength	1
65-10182	Force Controlled Solenoid Drives Microweld Tester	
65-10265	Weld Leaks Rapidly and Safely Detected	3
66-10220	Ultrasonic Recording Scanner Used for Nondestructive Weld Inspection	69
66-10289	Ultrasonic Hand Tool Allows Convenient Scanning of Spot Welds	73
66-10327	Inflatable Holding Fixture Permits X-Rays to be Taken of Inner Weld Areas	5
66-10577	Ultrasonic Water Column Probe Speeds up Testing of Welds	23
66-10587	Quality Control Criteria for Acceptance Testing of Cross-Wire Welds	2

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
67-10023	Tests Show That Aluminum Welds Are Improved by Bead Removal	33
67-10178	Fixture Facilitates Helium Leak Testing of Pipe Welds	43
67-10216	Electron Beam Welder X-Rays Its Own Welds	157
67-10359	Test Device Prevents Weld Joint Damage by Eliminating Axial Pin Forces on Unpotted Modules	1
67-10431	Camera Lens Adapter Magnifies Image	25
67-10542	Plastic Shoe Facilitates Ultrasonic Inspection of Thin Wall Metal Tubing	
68-10002	Gage Monitors Quality of Cross-Wire Resistance Welds	16
68-10004	Development of Mechanized Ultrasonic Scanning System	220
68-10333	Automatic, Nondestructive Test Monitors In-Process Weld Quality	75
68-10334	Microprobe Investigation of Brittle Segregates in Aluminum MIG and TIG Welds	27
68-10343	X-Ray Film Holder Permits Single Continuous Picture of Tubing Joint	7
69-10192	Detecting Hydrogen-Containing Contaminants on Metal Surfaces	4
69-10402	Nondestructive Testing of Welds on Thin-Walled Tubing	48
69-10418	Radiographic Threshold Detection Levels of Aluminum Weld Defects	
70-10081	Rene-41 Heat Treatment Electron Microscopy	
70-10084	Electrical Resistance Determination of Actual Contact Area of Cold Welded Metal Joints	
70-10189	Reference for Radiographic Film Interpreters	123

Tech Brief Number	Tech Brief Title	Number of Requestors for TSP's
70-10417	Testing of Brazed and Welded Connections of Stainless-Steel Tubing	1
70-10466	Nondestructive Assessment of Penetration of Electron-Beam Welds	8
70-10514	Ultrasonic Detection of Flaws in Fusion Butt Welds	

NOTE: The number of TSP Requestors for the Tech Briefs - which have no number given - is recorded as zero. However, many of these Tech Briefs are early ones (i.e., 63-64) during which time records of requests were not kept, or recent ones (i.e., 70-71) which are too new to have received requests.

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